LBL-10694
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Physical Review Letters

TWO-PROTON CORRELATION MEASUREMENTS IN 800- and 400-MeV/nucleon HEAVY-ION REACTIONS

I. Tanihata, M.-C. Lemaire, S. Nagamiya, and S. Schnetzer

March 1980

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

Two-Proton Correlation Measurements in 800- and 400-MeV/nucleon Heavy-Ion Reactions

I. Tanihata,[a] M.-C. Lemaire,[b] S. Nagamiya, and S. Schnetzer

Lawrence Berkeley Laboratory

University of California, Berkeley, California 94720

ABSTRACT

Energy and angular correlations of two protons emitted in collisions of C + C, C + Pb, Ne + NaF, Ar + KCl, at E^{Lab}_{Beam} = 800 MeV/A, and Ne + NaF at E^{Lab}_{Beam} = 400 MeV/A have been measured. A strong correlation due to p-p quasi-elastic scattering is observed except for C + Pb where nuclear shadowing is observed. A simple model is proposed to estimate the magnitude of the knock-out process in these heavy-ion collisions.

March 1980

Two-Proton Correlation Measurements in 800- and 400-MeV/nucleon Heavy-Ion Reactions

I. Tanihata,[(a)] M.-C. Lemaire,[(b)] S. Nagamiya, and S. Schnetzer

Lawrence Berkeley Laboratory

University of California, Berkeley, California 94720

In high-energy heavy-ion collisions, single-particle inclusive cross sections[1-3] have already given an overall picture of fragment emission to which several models such as the clean knock-out model[4] and thermal models[2,3,5-7] have been applied. These models, although they are quite different in their physical basis, describe certain aspects of the spectra, but further experimental studies are required in order to quantitatively test them. As pointed out in a previous paper,[1] p-p quasi-elastic scattering (p-p QES) is observed in C + C collisions. We have extended the measurement to several projectile and target combinations as well as to different beam energies in order to make a systematic study of the importance of clean knock-out processes. These results are described in the first part of the present paper. A simple model to estimate the contribution of the knock-out process is proposed in the second part. We also present experimental data pertaining to nuclear shadowing effects in C + Pb collisions.

The experimental system consisted of a magnetic spectrometer (S) and three sets of counter telescopes (R, U, and D). These telescopes were set at angles (θ,ϕ) = (40°, 180°), (40°, 90°), and (40°, 270°), respectively, with the beam being the z-axis. This θ-angle corresponds to ∿90° in the nucleon-nucleon c.m. frame. The spectrometer was located at $\phi = 0°$ and rotated between $\theta = 15°$ and 110°. Each telescope consisted of three plastic scintillators with absorbers sandwiched in between which allowed us to make a rough energy selection; a double coincidence corresponds to $E \gtrsim 100$ MeV and a triple coincidence selects $E \gtrsim 200$ MeV for protons. Although it was impossible to identify particles with the telescopes, it is known from the spectrometer data that the dominant yield at $\theta = 40°$ is protons. The solid angle of each telescope was 48 msr, subtending $\Delta\theta = 10°$.

We measured an azimuthal (or coplanar) correlation function $C_i(\theta, p)$ defined as

$$C_i(\theta,p) = 2 \frac{(S(\theta,p)\cdot R_i)/R_i}{(S(\theta,p)\cdot U_i)/U_i + (S(\theta,p)\cdot D_i)/D_i} \tag{1}$$

where θ is the scattering angle and p the momentum of the particle detected in the spectrometer, and i indicates the telescope energy cut: namely $i = 1$ for $E_{proton} \geq 100$ MeV and $i = 2$ for $E_{proton} \geq 200$ MeV. The quantity $(S(\theta,p)\cdot R_i)$ indicates the coincidence counts between the spectrometer and the R-telescope, and $R_i(U_i)$ indicates the single counts of the R(U)-telescope.

In Fig. 1 contour lines of the observed values of $C_2(\theta,p)$ are shown for collisions of C + C, Ar + KCl, and C + Pb at $E_{Beam}^{Lab} = 800$ MeV/A The data are displayed in the plane of $p_{\parallel}$ and $p_{\perp}$ in the nucleon-nucleon c.m. frame. In the cases of C + C and Ar + KCl the value of C_2 is always larger than 1 and has a peak right on the circle but on the opposite side of the cross hatched area. The data clearly show the existence of the p-p QES in C + C and Ar + KCl collisions. On the other hand, no peak is observed for C + Pb and the value of C_2 in this case is smaller than 1.

We first discuss the p-p QES component observed in light-mass nuclear systems. The observed maximum values of C_i's are summarized in Table I. We see that the C_i's are smaller for heavier-mass systems. The in-plane correlation is dominated by p-p QES, while the coincidence rate between two particles in general is proportional to the square of the total event multiplicity. Therefore the correlation function, C , approaches 1 as the event multiplicity increases. Experimental values of the average total charged-particle multiplicity, m, which were determined from the total inclusive yield divided by the total reaction cross section (σ_0), are listed in the 7th column of Table I These values of m are very close to the total nuclear charges of the participant piece calculated by the participant-spectator model,[2 8] as shown in the 8th column of the table. It is worthwhile to note that $(C_i - 1) \cdot m$ stays almost constant for all the systems. We also see that C_1(at peak) < C_2(at peak). This means that the lower-energy cut of the telescope includes more uncorrelated particles.

We now estimate the magnitude of the p-p QES component. We assume that the two-particle coincidence has two components; the p-p QES with a width characteristic of the Fermi momentum of the colliding nucleons and the azimuthally uncorrelated particles such as the particle through multiple scattering. We also assume all detected particles are protons. Under these assumptions, let us divide the inclusive cross section $(\frac{d\sigma}{d\vec{p}})$ into two parts: the p-p QES part $(\frac{d\sigma}{d\vec{p}})_{pp}$ and the remaining $(\frac{d\sigma}{d\vec{p}})_r$, where, in the former process, neither of the two protons is rescattered after one hard collision.

Because the multiplicities of the reaction play an important role, we rewrite the cross sections as

$$(\frac{d\sigma}{d\vec{p}}) = m(\frac{df}{d\vec{p}}), \quad (\frac{d\sigma}{d\vec{p}})_{pp} = m_{pp}(\frac{df}{d\vec{p}})_{pp} \text{ and } (\frac{d\sigma}{d\vec{p}})_r = m_r(\frac{df}{d\vec{p}})_r \qquad (2)$$

where m's represent the average multiplicities associated with the relevant processes and $(\frac{df}{d\vec{p}})$'s are spectral functions normalized to σ_0. Thus

$$m(\frac{df}{d\vec{p}}) = m_{pp}(\frac{df}{d\vec{p}})_{pp} + m_r(\frac{df}{d\vec{p}})_r$$
$$m = m_{pp} + m_r. \tag{3}$$

When a proton from the first term of the above equation (p-p QES proton) is detected at $\vec{p}_1$, (with the probability of $\frac{m_{pp}}{\sigma_0}(\frac{df}{d\vec{p}})_{pp}$), the probability of detecting another proton at $\vec{p}_2$ is proportional to $[D(\vec{p}_1,\vec{p}_2) + \frac{(m-2)}{0}(\frac{df}{d\vec{p}_2})]$ where $D(\vec{p}_1,\vec{p}_2)$ is the probability that the QES partner of the detected proton at $\vec{p}_1$ scatters to $\vec{p}_2$ with normalization $\int D(\vec{p}_1,\vec{p}_2)d\vec{p}_2 = 1$. The second term arises from random coincidences. Similarly, when a proton from the second term in Eq. (3) is detected at $\vec{p}_1$ with $\frac{m_r}{\sigma_0}(\frac{df}{d\vec{p}_1})_r$, the probability of detecting another proton at $\vec{p}_2$ is proportional to $\frac{(m-1)}{\sigma_0}(\frac{df}{d\vec{p}_2})$. Thus, the two-proton inclusive cross sections can be written as

$$\frac{d^2\sigma}{d\vec{p}_1 d\vec{p}_2} = m_{pp}(\frac{df}{d\vec{p}_1})_{pp}\left[D(\vec{p}_1,\vec{p}_2) + \frac{(m-2)}{\sigma_0}(\frac{df}{d\vec{p}_2})\right] + m_r(\frac{df}{d\vec{p}_1})_r\frac{(m-1)}{\sigma_0}(\frac{df}{d\vec{p}_2}). \tag{4}$$

The correlation function $C_2(\theta,p)$, defined in Eq. (1), then is written as

$$C_2(\theta,p) - 1 = \frac{m\sigma_0}{\int \frac{d\sigma}{d\vec{p}_R}d\vec{p}_R}\ \frac{\alpha\int D(\vec{p},\vec{p}_R)d\vec{p}_R}{(m-1) - \alpha} \tag{5}$$

where integration is over the momentum covered by the R-telescope and $\alpha \equiv (\frac{d\sigma}{d\vec{p}})_{pp}/(\frac{d\sigma}{d\vec{p}})$ is the fraction of p-p QES cross section which in general depends on p_1. Because we restrict our discussion to a narrow kinematical region near QES, we assume that α is constant. In the extreme case where all the protons are emitted via single nucleon-nucleon collisions without further multiple scattering, α has its maximum value $\alpha_0 = 0.43$.[9]

Fig. 2 shows the calculated value of $(C_2(40°,p) - 1)$ (solid line) based on Eq. (5) for the C + C data. The function $\int D(\vec{p}\cdot\vec{p}_R)d\vec{P}_R$ was calculated using our experimental geometry with a Monte Carlo method, assuming that nucleons have a Gaussian momentum distribution $(e^{-p^2/(177 \text{ MeV/c})^2})$ both in the target and the projectile. This distribution is very close to that obtained from a many-body theory with a Reid soft core potential.[11] The shape of $(C_2(40°,p) - 1)$ is reproduced well. However, if we use $\alpha = \alpha_0$, the amplitude is six-times larger than the experiment, which indicates that both single and multiple scatterings are involved in these collisions. The observed fraction α/α_0 is summarized in the 9th column of Table I. They are essentially the same within an error for all combinations.

In the analysis we assumed that the observed azimuthal correlations are due only to p-p QES. This simplified model neglects residual correlations of secondary scattered particles and also neglects correlations associated with energy-momentum conservation of the whole or of a sub-system (except a two-particle system). Our rough estimate for this process shows that these effects are unlikely to change $(C_2 - 1)$ by more than 20%. The observed correlations can also be influenced by nuclear shadowing, which gets progressively more important as the masses of the colliding nuclei increase. Quantitative discussion of this effect is, however, left as a subject for the future.

Let us compare the fraction α/α_0 to the fraction P of single collision in an inclusive proton spectrum. A distinction should be made between α/α_0 and P, because, in the former, none of the particles after NN collisions are rescattered, whereas, in the latter, the detected proton was not rescattered but the other particles involved in the collision could be. Thus the fractions

α/α_0 and P are related by $P^2 \simeq \alpha/\alpha_0$. The resulting fraction P is listed in the last column of Table I. This value of P is comparable to the value obtained from the high-multiplicity biased data for Ar + KCl.[12]

In conclusion, for light-mass nuclear collisions, two coplanar correlations have been used to estimate the fraction of the single NN collision component P in a limited kinematical region ($\theta_{CM} \sim 90°$, $P_{CM} \sim P_{CM}(\mathrm{Beam})/A$) for protons. P $\sim$ 50% was obtained from the present analysis. Because of several assumptions involved in the analysis, the estimated values of P are thought to have 30 - 40% errors in them.

Finally let us say a few words on the observed anti-coplanarity for a heavy-mass target. As shown in Fig. 1 for 800 MeV/nucleon C + Pb, the ratio C_2 is smaller than 1, and, furthermore, a valley extends toward $\theta^{c.m.} \sim 60°$. This observation can be qualitatively understood in terms of nuclear shadowing. When we detect the first proton with the spectrometer, then the reaction region is effectively biased toward that part of the Pb nuclear surface that is facing in the direction of the spectrometer. It is then rather difficult for the second proton to be emitted in the opposite direction from the first proton, namely in the R-telescope direction, because the second proton has to penetrate a large amount of nuclear matter. On the other hand, it is relatively easy for the second proton to be emitted in the up or down direction. This causes C_2 to be smaller than 1.

The authors would like to thank Professors O. Chamberlain, G. Shapiro, H. Steiner, and Mr. R. Fuzesy for their help and encouragement throughout this work, and Drs. R. L. Hatch, E. Moeller and Y. Shida for their stimulating discussion. This work is supported by the Nuclear Science Division of the U. S.

Department of Energy, under Contract W-7405-ENG-48, the Yamada Foundation, and by the INS-LBL Collaboration Program.

REFERENCES

(a) On leave from INS, University of Tokyo, Tokyo, Japan.

(b) Present address: DPhNME, CEN Saclay, 91190 Gif-sur-Yvette, France.

1. S. Nagamiya et al., Phys. Lett. 81B, 147 (1979).

2. G. D. Westfall et al., Phys. Rev. Lett. 37, 1201 (1976).

3. J. Gosset et al., Phys. Rev. C16, 629 (1977).

4. R. L. Hatch and S. E. Koonin, Phys. Lett. 81B, 1 (1978).

5. J. Gosset, J. I. Kapusta, and G. D. Westfall, Phys. Rev. C18, 844 (1978).

6. S. Das Gupta, Phys. Rev. Lett. 41 1450 (1978).

7. A. Z. Mekjian, Nucl. Phys. A312, 491 (1978).

8. J. Hüfner and J. Knoll, Nucl. Phys. A290, 460 (1977).

9. We used the value calculated using the clean-knock-out model; R. L. Hatch, private communication, 1979.

10. A. S. Goldhaber and H. H. Heckman, Ann. Rev Nucl. Sci. 28, 161 (1978).

11. J. D. Zabolitzky and W. Ey, Phys. Lett. 76B, 527 (1978).

12. S. Nagamiya et al., Lawrence Berkeley Laboratory report LBL-10693 (1980) (to be published).

TABLE I. Value of C_i at peak position and average charged-particle multiplicity, m, for light-mass nuclear collisions. Fraction of the single clean-knock-out component is listed in the last column.

E_{Beam}^{Lab} (MeV)	Reaction	C_2(at peak)	C_1(at peak)	$\sigma_{inclusive}^{a)}$ (barn)	$\sigma_0^{b)}$ (barn)	m		$\alpha/\alpha_0^{d)}$	$p^{d)}$
						$\frac{\sigma_{inclusive}}{\sigma_0}$	PS-model$^{c)}$		
	C + C	1.75±0.07	1.55±0.06	2.8±0.6	0.80	3.5±0.7	3	0.20±0.07	0.45±0.10
800	Ne + NaF	1.40±0.10	1.35±0.08	7.7±1.6	1.30	5.9±1.2	5	0.21±0.09	0.46±0.10
	Ar + KCl	1.25±0.10	1.16±0.10	23±5	2.45	9.4±1.8	9	0.23±0.12	0.48±0.16
400	Ne + NaF	1.50±0.07	1.40±0.06	5.2±1.2	1.30	4.0±0.9	5	0.24±0.10	0.49±0.13

a) The total yield of charges calculated from the inclusive data taken at $10° < \theta < 145°$, after the extrapolation to 0° and 180°.

b) Total reaction cross section [Ref. 10].

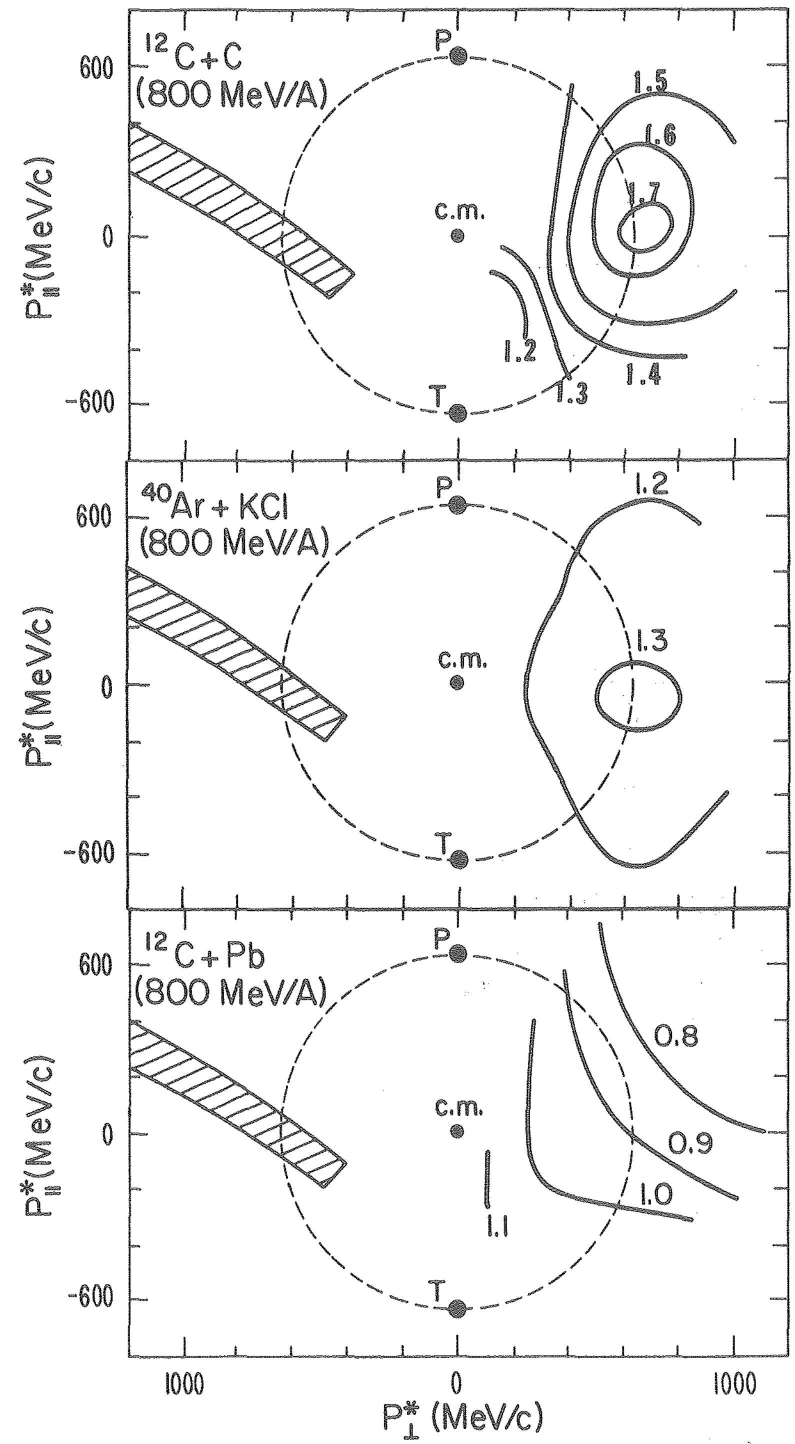
c) Calculated nuclear charges for the participant piece calculated from the participant spectator model.

d) Errors quoted here are statistical only.

FIGURE CAPTIONS

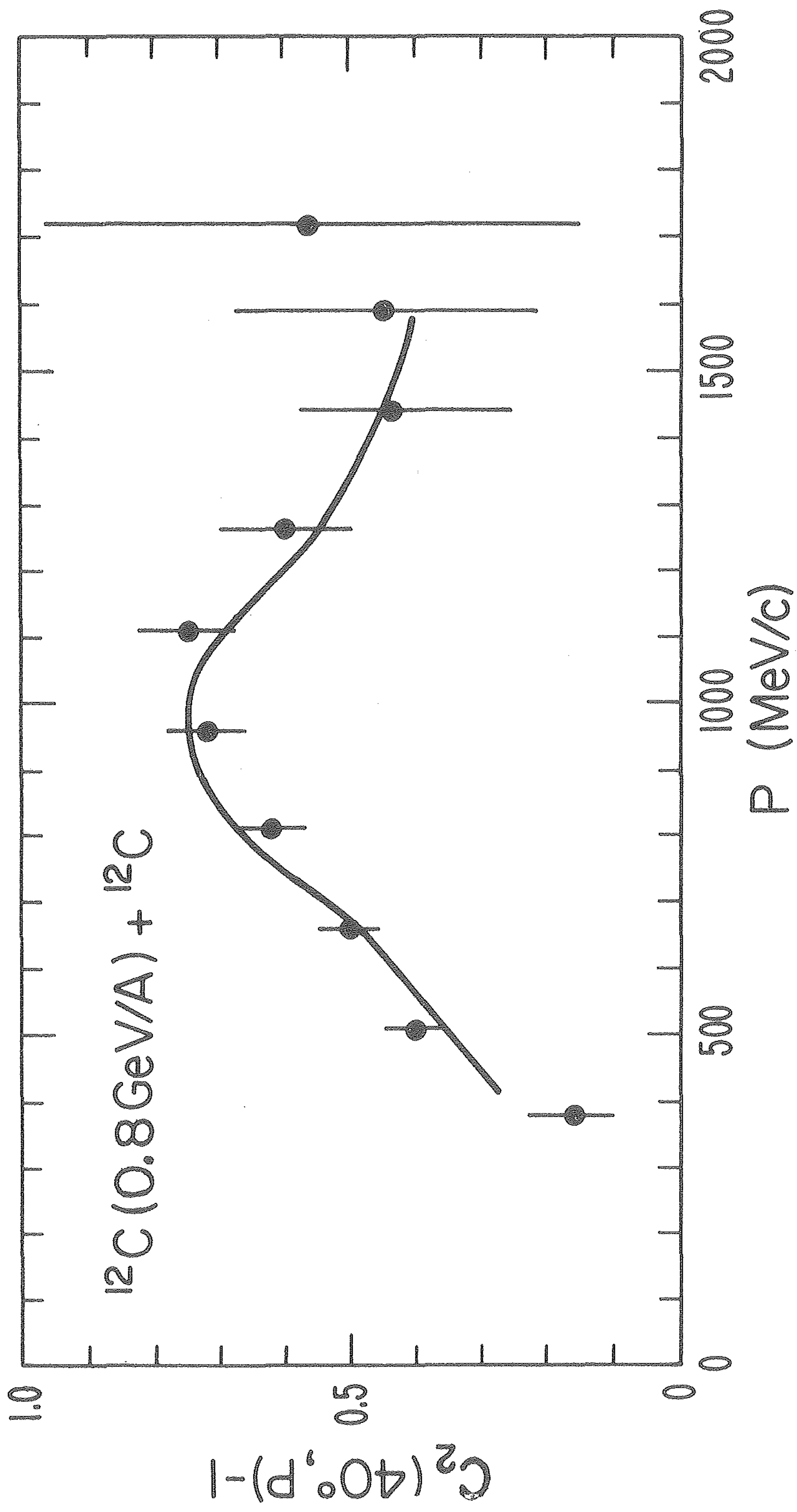
Fig. 1 Contour plot of C_2 defined by Eq. (1) for C + C, Ne + NaF, and Ar + KCl at E_{Beam}^{Lab} = 800 MeV/nucleon. P and T indicate projectile and target momenta per nucleon, respectively, in the nucleon-nucleon c.m. frame. The dashed circle indicates the free proton-proton elastic scattering kinematics, and the cross-hatched area shows the kinematical region of protons detected by the R-telescope.

Fig. 2 Fit of $C_2(40^\circ,p)$ as a function of p, using a gaussian internal momentum distribution of nucleons inside the nucleus.



XBL 793-758B

Fig. 1



XBL 793-765

Fig. 2